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Water Resources Research

RESEARCH ARTICLE

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Key Points:

- A novel application of real options analysis to a realistic case provides insight into benefits and limitations of the method in practice
- Challenges in the case study are geographical details, a large ensemble of scenarios and the inclusion of stakeholder preferences
- The value of robustness and flexibility of flood risk management strategies including dikes and room for the river measures are evaluated

Supporting Information:

- Supporting Information S1

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Benefits and Limitations of Real Options Analysis for the Practice of River Flood Risk Management

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Abstract Decisions on long-lived flood risk management (FRM) investments are complex because the future is uncertain. Flexibility and robustness can be used to deal with future uncertainty. Real options analysis (ROA) provides a welfare-economics framework to design and evaluate robust and flexible FRM strategies under risk or uncertainty. Although its potential benefits are large, ROA is hardly used in today's FRM practice. In this paper, we investigate benefits and limitations of a ROA, by applying it to a realistic FRM case study for an entire river branch. We illustrate how ROA identifies optimal short-term investments and values future options. We develop robust dike investment strategies and value the flexibility offered by additional room for the river measures. We benchmark the results of ROA against those of a standard cost-benefit analysis and show ROA's potential policy implications. The ROA for a realistic case requires a high level of geographical detail, a large ensemble of scenarios, and the inclusion of stakeholders' preferences. We found several limitations of applying the ROA. It is complex. In particular, relevant sources of uncertainty need to be recognized, quantified, integrated, and discretized in scenarios, requiring subjective choices and expert judgment. Decision trees have to be generated and stakeholders' preferences have to be translated into decision rules. On basis of this study, we give general recommendations to use high discharge scenarios for the design of measures with high fixed costs and few alternatives. Lower scenarios may be used when alternatives offer future flexibility.

Plain Language Summary Worldwide, large amounts of money are needed to protect growing populations against increasing flood risks. Decisions on flood risk management measures are often difficult because the future is uncertain, resulting in possible over- or underinvestments. Integrating flexibility or robustness in the decisions are two different ways to deal with this. Real options analysis (ROA) can help to design and evaluate robust and flexible strategies but is hardly used. We examine benefits and limitations by applying ROA to a realistic case study in the Netherlands. We develop robust dike investment strategies and value the flexibility offered by room for the river measures. The ROA for the realistic case study needs a high level of geographical detail, a large number of future scenarios, and the inclusion of stakeholders' preferences. Limitations are the complexity, the recognition and quantification of uncertainty, and the mapping of possible decisions in time. ROA provides relevant insights for policy makers which can not be reached with standard cost-benefit analysis: first: use high scenarios for the design of measures with high fixed costs (like dikes), and second: the value of flexibility due to room for the river measures increases with uncertainty.

1. Introduction

Especially in urbanized deltas, present-day flood risks are high and, if no actions are taken, will continue to increase in the future due to population growth, climate change, and soil subsidence (e.g., Winsemius et al., 2016). The costs of measures needed to protect those deltas are estimated in the order of tens of billions of US\$/yr (Hinkel et al., 2014; Ward et al., 2017). The majority of these measures, such as dikes, dams, and barriers, have high upfront investment costs which are sunk, have long life times, and are expensive to adapt to changing conditions. For decisions on such investments, the future climate and socioeconomy should thus be considered. This introduces a high degree of uncertainty, making decisions complex. But by

integrating future uncertainty in the decision-making process, efficiency gains of millions, if not billions of US\$ may also be achievable in flood risk management, allowing more people and property to be protected against floods within the same tight budget.

In this paper, we distinguish two different ways to integrate future uncertainty in investment decisions: aiming at robustness and aiming at flexibility. With robustness, we mean the ability to endure change without having to adapt, while with flexibility, we refer to the ability to adapt to change (Husdal, 2010). For flood risk management, an example of a robust decision is to invest in a large flood protection measure at once. An example of flexibility is the decision to start with a small measure which is easy to modify in future. The value of such robustness and flexibility depends on the amount of uncertainty, the cost-structure of the measures (fixed and variable costs), and the discount rate which is used to compare present with future costs and benefits. While robustness may lead to overengineered measures and hence regret under low risk scenarios, flexibility may result in missed economies of scale and hence regret under high risk scenarios. One way of deriving the value of flexibility is thus by comparing costs and benefits of a flexible investment strategy with those of a less flexible, that is, a more robust strategy. In such comparison, a negative value for flexibility would indicate a positive value for robustness. Following those definitions, robustness and flexibility are two sides of the same coin. Those definitions are different from those used in the recent robust decision making and decision making under deep uncertainty literature, where flexibility is considered as means to design a robust management strategy—a strategy which performs relatively well under a wide range of scenarios, by having the built-in flexibility to adapt (e.g., Herman et al., 2015; Lempert et al., 2006).

Different methods have been developed to support decision making under risk and uncertainty, which can be applied to investments for climate adaptation, like flood risk management. For overviews of these methods, see e.g. Hallegatte et al. (2012) and Watkiss et al. (2015). Real options analysis (ROA) is a method which can be used within the welfare-economics framework of cost-benefit analysis (CBA) or cost-effectiveness analysis (CEA) and is able to capture the value of flexibility explicitly. ROA, which originates from corporate finance, aims to value the flexibility a “real” option can offer. Examples of real options are future possibilities to expand, shrink, delay, speed up, or terminate investments in real physical assets. In real options analysis, optimal here-and-now decisions and values of future wait-and-see options can be determined jointly. The word “optimal” refers to the decision with the lowest expected present value of the costs (in case ROA is an extension of a CEA) or highest expected net present value (in case ROA is an extension of a CBA). ROA thus assumes risk-neutral preferences, which is appropriate to value *effectiveness* uncertainty of most public investment decisions (Arrow & Lind, 1970; Kaufman, 2014; Kind et al., 2017).

In reality, it is often complex to conduct ROAs. First, probabilities for the uncertain parameters are required. Note that—based on Knight’s formal distinction between risk (measurable) and uncertainty (not measurable; Knight 1921)—this would mean that ROA can only be applied to decisions under risk, not uncertainty. In the ROA literature, however, such a distinction is not always made (e.g., Schwarz & Trigeorgis, 2001), and in practice often subjective probabilities for the uncertain variables are being used, making the distinction between risk and uncertainty less clear. We therefore do not distinguish risk from uncertainty throughout this paper. Second, solving ROAs may be complex. Although some ROA problems can be solved using Black-Scholes equations or simulation (de Neufville & Scholten, 2001; Schwarz & Trigeorgis, 2001), ROAs which consider a sequence of multiple, often dependent options normally require that the uncertainty and possible decisions are discretized into scenario and decision trees (see e.g., Gersonius et al., 2012; Wang & de Neufville, 2005), which may be hard to specify.

Today, few papers published in peer reviewed journals describe the application of ROA in the water and flood risk management domain. In supporting information Table S1, we reviewed the flood risk management cases (Abadie et al., 2017; Buurman & Babovic, 2016; Cunha et al., 2014; de Bruin, 2011; Deng et al., 2013; Gersonius et al., 2013; Hino & Hall, 2017; Kontogiannia et al., 2014; Linquiti & Vonortas, 2012; Manocha & Babovic, 2016; Ryu et al. 2017; van der Pol et al., 2017; Woodward et al., 2011, 2014). Those are all (semi-) hypothetical, consider a few stylized measures and use relative simple scenario and decision trees, which hampers the support of decisions in flood risk management in practice. ROA is thus seldom used to support actual flood risk management decisions. Rather, CBA is the most commonly used method (Mechler et al., 2014). In its most simple form, a CBA evaluates in terms of social welfare all costs and benefits of a now-or-never investment decision for a most likely future. More advanced CBAs also consider the optimal size and timing of a sequence of investments (e.g., Eijgenraam et al., 2014; Kind, 2014), while scenario based cost-

benefit analyses (SBCBAs) evaluate investment decisions for separate future scenarios (e.g., Frontier Economics, 2013). The distinct feature of ROA is that it integrates future uncertainty and separates optimal here-and-now from future wait-and-see decisions in the analysis.

Given the few ROA applications, in this paper, we ask two questions. First, compared to a CBA, what additional insights does ROA give, and can this lead to different project decisions? Second, what is needed to perform ROA in a flood risk management context in practice, and is this feasible?

This first question is not entirely new, nor is its answer. In section 2, we show with a simple example how ROA would recommend to accept a flood risk management project, while CBA would recommend to reject it. This example illustrates the potential value of ROA for flood risk management decisions. It also serves as introduction to an illustrative case study, which sheds light on the second question. The case concerns the application of ROA to an entire river branch of the river Rhine, using realistic and very detailed data. The data originate from the Dutch Delta Programme and concern the river IJssel, where investments of €3–5 billion are needed to safeguard flood protection throughout this century. The policy question is, which part of the flood protection tasking should be filled in with dike reinforcements, and which part with “room for the river” measures? The case study, model and results are discussed in sections 3–5.

In discussion section 6, we reflect on lessons learned from the example and case study. Moreover, we highlight three features which were needed for this novel application of ROA to a very realistic case study: the large number of scenarios, the geographical detail, and the inclusion of stakeholder preferences. We also discuss the relevance of this ROA approach for international flood risk management, and its limitations. Section 7 concludes.

2. The Benefit of ROA for Flood Risk Management, Illustrated With a Simple Example

We highlight with a simple example the benefit of using ROA instead of CBA to support decision making on flood risk management. We assume that the capacity of a river system must be sufficient to convey a “design discharge” without flooding and that policy has decided to increase the value of this discharge in 2020 from 15,000 to 16,000 m³/s. Dikes must be heightened as a consequence. Future increases of the design discharge are also possible, but uncertain. The first question is to what extent dikes should be designed in 2020 to account for this possible future increase.

For the design discharge in 2040, three scenarios exist: the low scenario, with a 25% probability of a discharge of 16,000 m³/s; the middle scenario, with a 50% probability of a discharge of 17,000 m³/s; and the high scenario with a 25% probability of a discharge of 18,000 m³/s. ROA is used to identify the optimal design in 2020, i.e., the design which leads to the lowest expected value of the discounted cost over the period 2020–2040.

Fixed dike costs are \$7 and variable dike cost \$1 per 1,000 m³/s increase of the design discharge. Hence, costs to heighten dikes to accommodate an additional 1,000, 2,000, or 3,000 m³/s are \$8, 9, and 10. Table 1 illustrates that with a discount rate of 4.5%/yr, it is optimal to design the dikes in 2020 to accommodate a discharge of 17,000 m³/s. This leads to the lowest expected present value of the costs of \$9.8. The investment in 2020 is \$9. If the discharge increases in 2040 to 18,000 m³/s, the additional investment is \$8.

Now stakeholders propose a room for the river measure with a capacity of 1,000 m³/s, to be implemented if the 2040 discharge reaches 17,000 m³/s or more. Costs and benefits of this proposal need to be evaluated. Table 2 illustrates that with the proposal, the optimal dike design in 2020 would be to accommodate a discharge of 16,000 m³/s. In this case, the expected present value of the dike investments is \$8.8. In case the discharge reaches 18,000 m³/s, the additional dike investment is \$8.

The cost of the room for the river measure in 2020 is \$3, which reduces to a present value of \$1.24 if the measure is taken in 2040 in the middle or high scenario, which has a probability of 75%. Hence, the expected present value of the cost of the room for the river option is $0.75 \times 1.24 = \$0.93$. Savings in the present value of the optimal dike investments are $9.8 - 8.8 = \$1.0$. The room for the river option has a benefit-cost ratio of $1.0 / 0.93 = 1.07$ and an option value of $1.0 - 0.93 = \$0.07$. Although at the margin, ROA indicates that the room for the river option is valuable and should be accepted. Note that due to the room for the river measure, the number of possible decisions in 2040 increases. The measure thus adds flexibility, which turns out to be valuable.

Table 1

Dike Investments for Different Values of the Design Discharge

| The discharge for which the dikes are designed in 2020 (m ³ /s) | Dike investments 2020 (\$) | Design discharge 2040 (m ³ /s) | Probability design discharge 2040 (%) | Dike investments 2040 (\$) | Present value dike investments (2020 + 2040) (\$) | Expected present value of dike investments (\$) |
|--|----------------------------|---|---------------------------------------|----------------------------|---|---|
| 16,000 | 8 | 16,000 | 25 | 0 | 8 | 10.6 |
| 16,000 | 8 | 17,000 | 50 | 8 | 11.3 | 10.6 |
| 16,000 | 8 | 18,000 | 25 | 9 | 11.7 | 10.6 |
| 17,000 | 9 | 16,000 | 25 | 0 | 9 | 9.8 |
| 17,000 | 9 | 17,000 | 50 | 0 | 9 | 9.8 |
| 17,000 | 9 | 18,000 | 25 | 8 | 12.3 | 9.8 |
| 18,000 | 10 | 16,000 | 25 | 0 | 10 | 10 |
| 18,000 | 10 | 17,000 | 50 | 0 | 10 | 10 |
| 18,000 | 10 | 18,000 | 25 | 0 | 10 | 10 |

Now let us use a scenario based cost-benefit analysis (SBCBA) to assess the value of the proposed measure. In the high scenario, the present value of the dike costs in 2020 would be \$10 without and \$9 with the room for the river measure (see Table 1), hence dike costs of \$1 would be saved, while the present value of the cost of the room for the river measure would be \$1.24. The benefit-cost ratio of the room for the river measure is $1/1.24 = 0.81$ and the net present value negative \$0.24. The benefit-cost ratio and net present value are the same in the middle scenario. In the low scenario, the discharge does not increase and the room for the river measure is not needed. Hence, a SBCBA would recommend to reject the proposed room for the river measure.

The example highlights the various benefits of a ROA. First, ROA identifies the optimal here-and-now design of the dikes in 2020, while the SBCBA does not. Second, ROA integrates the option value of the room for the river measure, which changes the optimal here-and-now dike decision. ROA recommends to accept the room for the river option and to reduce short-term dike investments. Note that the room for the river option only pays-off if the future design discharge does not increase and there is no need to exercise it. In this case, short-term dike costs have been saved, while eventually no cost for implementing the room for the river measure is incurred. This is favorable: budgets saved on dikes and room for the river measures can be used for other locations where flood risks are high, or for other purposes.

3. Description of the IJssel Case Study

The simple example of the previous paragraph has clearly demonstrated the potential value of ROA for flood risk management decisions. The question now becomes how feasible it is to conduct such ROA in practice. We

Table 2

Dike Investments for Different Values of the Design Discharge, Assuming That a Room for the River Measure Will Be Taken if the Discharge Reaches 17,000 m³/s

| The discharge for which the dikes are designed in 2020 (m ³ /s) | Dike investments 2020 (\$) | Design discharge 2040 (m ³ /s) | Probability design discharge 2040 (%) | Dike investments 2040 (\$) | Present value dike investments (2020 + 2040) (\$) | Expected present value of dike investments (\$) |
|--|----------------------------|---|---------------------------------------|----------------------------|---|---|
| 16,000 | 8 | 16,000 | 25 | 0 | 8 | 8.8 |
| 16,000 | 8 | 17,000 | 50 | 0 | 8 | 8.8 |
| 16,000 | 8 | 18,000 | 25 | 8 | 11.3 | 8.8 |
| 17,000 | 9 | 16,000 | 25 | 0 | 9 | 9 |
| 17,000 | 9 | 17,000 | 50 | 0 | 9 | 9 |
| 17,000 | 9 | 18,000 | 25 | 0 | 9 | 9 |

contribute to this discussion by using an illustrative, realistic ROA case study originating from the Delta Programme in the Netherlands.

3.1. Case Study Description

In the case study, different flood protection strategies for the IJssel branch of the river Rhine have to be evaluated. The areas along this river are protected by about 250 km dikes, with an average height of 3.4 m. Those dikes have to meet legal flood protection standards—flood probabilities ranging for different locations along the IJssel between 1/300 and 1/10,000 per year (van Alphen, 2016).

At present, the IJssel dikes are high but not strong enough and are in urgent need of strengthening (Schielen & van den Aarsen, 2014). According to the Delta Programme, dikes will also have to be heightened before the end of the century with a maximum of on average about 50 cm, due to increases in extreme river discharges and due to soil subsidence. Various room for the river measures, such as lowering or removing obstacles from the floodplains and digging bypasses, have been proposed as alternative for part of the dike increases (Rijke et al., 2012). Those measures lower water levels (also upstream and downstream of its location), and hence reduce the required investments for dike heightening, but cannot prevent the required short-term strengthening of dikes. The question in the Delta Programme is how much of the future tasking should be filled in with dike investments, and how much with room for the river measures. To answer this question, different strategies combining dikes with a few or with more room for the river measures are being evaluated (Delta Programme, 2014). As in many other countries, economic analyses (CBA and CEA) play an important role in this evaluation (Bos & Zwaneveld, 2017; Mechler et al., 2014).

In the case study, we consider two strategies: a dike strategy, and a “preferential” strategy in which dikes and room for the river measures are combined, see Figures 1 and 2. Note that in the actual Delta Programme, also other combinations are being evaluated, but that those are not needed to illustrate our case study. While the dike strategy is likely to be the most cost-efficient to meet and maintain the flood protection standard (Bos & Zwaneveld, 2017; de Bel, 2014; Ebregt et al., 2005), room for the river measures also generate cobenefits, such as recreation, nature, and spatial quality, and are therefore often preferred by local stakeholders (Deltaprogramma Rijn, 2016). Due to data limitations, updates and work-in-progress in the Delta Programme, the dike and preferential strategy in this case study are based on—but not identical to—the dike and preferential strategies in the Delta Programme, and results are only meant to illustrate the ROA application. All data on costs and benefits of dikes and room for the river measures are however “real” and were received from the Delta Programme. The information on the dikes is very detailed; the Delta Programme distinguishes 283 dike segments along the IJssel with an average length of about 1 km (van der Meij et al., 2016; van Vuren et al., 2017). The information is described in supporting information Text S1, Figures S1–S3, and Tables S2 and S3.

3.2. Uncertainty and Scenarios for the Design Discharge

The objective of applying a ROA to the river IJssel would be to support decisions on flood risk management in light of the uncertainty about the future design discharge. In this section, we discuss this discharge uncertainty.

The design discharge is the maximum discharge a river can convey without causing floods, and is valid for a given return period. It is used in many countries to determine the required height of the dikes, and is based on an extrapolation of measured and/or modeled discharges. Especially for higher return periods, the uncertainty of the existing value of the design discharge is already substantial. This uncertainty stems from various sources, and includes the uncertainty due to the extrapolation of relative short time series of river discharge or climate data of 50–100 years to extreme events with return periods of for example 1,000 or 10,000 years, the uncertainty due to imperfect knowledge of the behavior of river systems under extreme conditions, and the uncertainty about human interventions during extreme events in upstream areas (e.g., like sand bagging or the use of water retention areas; Diermanse et al., 2010; Hegnauer et al., 2014, 2015; Kjeldsen et al., 2008; Prinsen et al., 2015). Because of this uncertainty and its importance for designing flood protection measures, changing the value of the design discharge is a policy decision in many countries. For reasons of policy consistency, it is not desirable to change this discharge frequently. For the Rhine, Table 3 shows how and why the design discharge changed in history. As the table illustrates, during the last 90 years, the design discharge was changed 5 times, remarkably more often downward than upward.

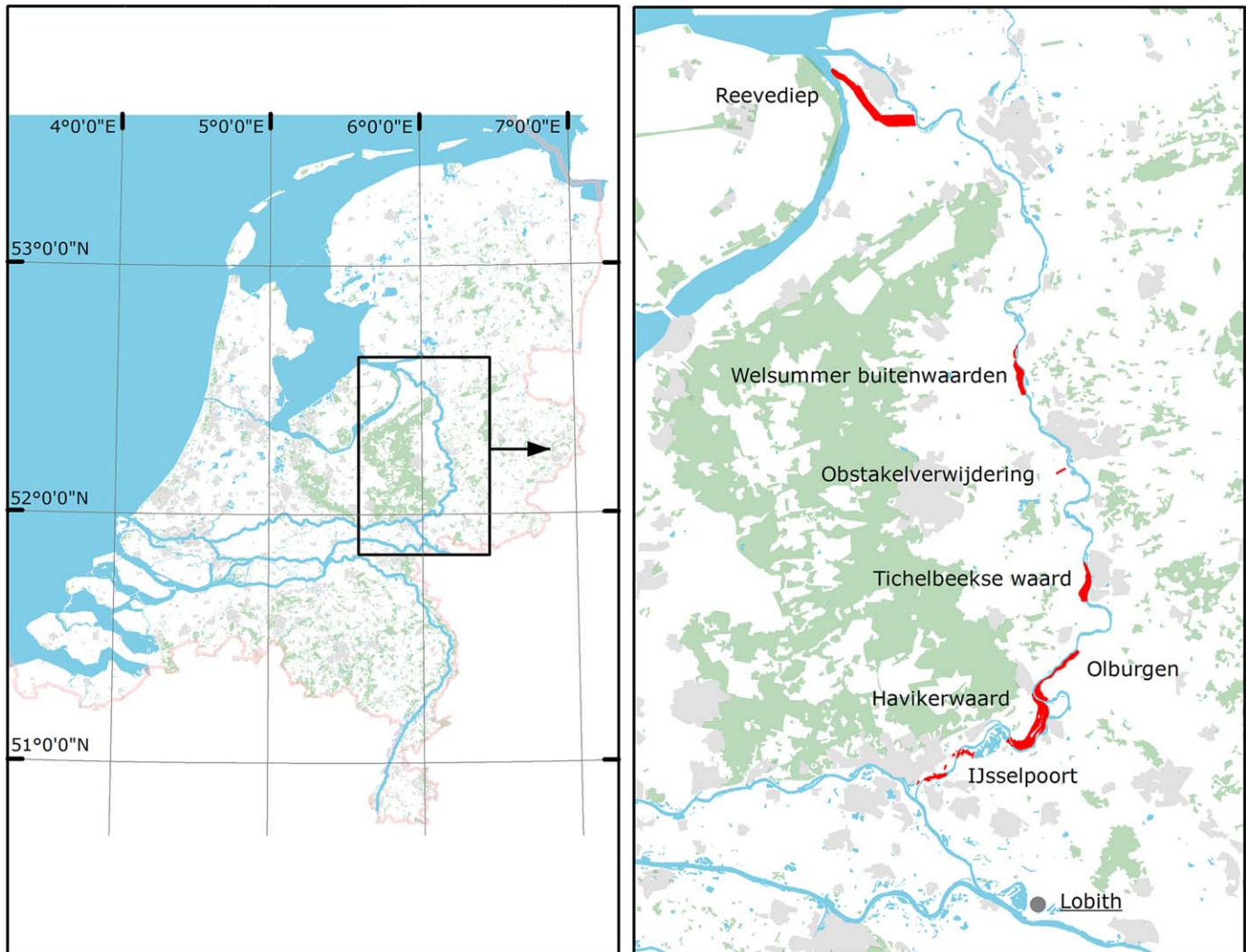


Figure 1. Map of the IJssel case study area and location of room for the river measures in the illustrative case study.

The uncertainty of the value of the future design discharge is of course larger than the uncertainty of the present one. Additional sources of uncertainty include: improving or changing the method for determining the design discharge (see also Table 3), the effects of future upstream flood protection policies and measures, the impact of scenarios for climate change and the regular updates of these scenarios, the limited possibilities for the statistical detection of the impact of climate change, the erosion of the riverbed, and the possible future update of flood protection standards (Cramer et al., 2014; Delta Programme, 2014;

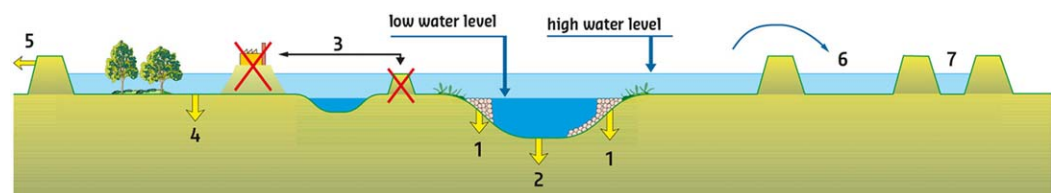


Figure 2. Typology of room for the river measures (Reevediep, type 7; Welsummer buitenwaarden and Tichelbeekse waard, type 4; Obstakelverwijdering, type 3; Olburgen, Havikerwaard and IJsselpoort, types 3 + 4).

Table 3
Historical and Current (Design) Discharges for the Rhine

| Period | (Design) discharge (m ³ /s) | Standard or return period (1/yr) | Reason for change |
|-----------|--|----------------------------------|--|
| 1926–1956 | 13,500 | | Highest measured historical discharge (1926) |
| 1956–1975 | 18,000 | 1/3,000 | 1953 floods; installation of the first Delta Commission which introduced statistical methods for extrapolation of measured discharges and legal flood protection standards |
| 1975–1993 | 16,500 | 1/1,250 | Lower legal standard after civil protests about dike improvements |
| 1993–2001 | 15,000 | 1/1,250 | New statistical methods introduced after civil protests about dike improvements |
| 2001–2017 | 16,000 | 1/1,250 | High river discharges in 1993 and 1995 |
| 2017 | 15,000 | 1/1,250 | Introduction of a new method (GRADE) to simulate river discharges based on climate, hydrological and hydraulic modeling |
| | 16,000 | 1/10,000 | |

Note. On the basis of RIVM (2004, p. 43), 2017 rounded figures on basis of Prinsen et al. (2015). Unrounded figures for 2017 are 14,970 and 16,270 m³/s, respectively.

Diermanse et al., 2010; Haasnoot et al., 2015; Hegnauer et al., 2015; Kind, 2014; Klijn et al., 2015; KNMI, 2014; Sperna-Weiland et al., 2015; Wilby et al., 2008). Each of these sources can change the value of the future design discharge upward, and some also downward (supporting information Table S4).

In the Netherlands, no formal approach exists to integrate these sources of uncertainty into values for the future discharge used for policy making. In the official Delta scenarios, the uncertainty in the development of extreme future discharges is only due to the uncertainty of the impact of climate change (Bruggeman et al., 2013; Klijn et al., 2015; Sperna-Weiland et al., 2015). For the Rhine in the Netherlands, this climate impact is believed to be low due to the limited discharge capacity of the Rhine in Germany: floods in Germany are expected to reduce extreme river discharges before they reach the Netherlands (ENW, 2016). This results in relatively small differences between the high and low scenarios for the extreme discharge of the Rhine at Lobith. As a result, often only the high scenario is used to develop and evaluate flood risk management strategies (e.g., Deltaprogramma Rijn, 2016; van Vuren et al., 2017).

If there is no recognition of the uncertainty about the future, there is no need to aim for robustness or flexibility, and no need for ROA. However, not climate change, but other causes were reasons in the past to change the design discharge for the Rhine (see Table 3 and Diermanse et al. (2010)). Note that such other causes for changing the design discharge also apply to many locations elsewhere, for example to the river Brisbane (Queensland Floods Commission of Inquiry, 2012; Syme et al., 2017) and to the ungauged rivers in the UK (Wilby et al., 2008).

Acknowledging and quantifying a broad range of uncertainty is critical to a ROA. There is however no scientific approach to integrate the identified sources and magnitudes of uncertainty into a discrete set of scenarios which perfectly represents the range of underlying uncertainty (Carlsen et al., 2016; Defourny et al., 2011). Integration and discretization are simplifications which are needed and have to be based on subjective choices and expert judgement. This makes ROA vulnerable to criticism, and sensitivity analysis is indispensable to show the robustness of results.

For our case study, we carefully developed an ensemble of scenarios for the extreme discharges which we consider plausible and diverse, with probabilities attached to each scenario (see supporting information Text S2). The ensemble is created for the illustrative purpose of this paper only, and has not been verified by official flood risk management authorities. It is based on two assumptions. First, it assumes that during the planning period up to 2140, the change in the extreme discharges at Lobith relative to the present extreme discharge ranges between $-1,000$ and $+4,000$ m³/s. For example, the 10,000 year discharge of at present 16,000 m³/s (used in the Delta Programme as the *reference discharge* and henceforth also referred to as *extreme discharge*, *design discharge*, or just *discharge*) ranges in the future between a minimum of 15,000 m³/s and a maximum of 20,000 m³/s. The minimum could be the result of, e.g., a change in the extrapolation method and the failure to detect the impact of climate change, and the maximum of, e.g., detection of climate change, a change in the extrapolation method, a change in upstream flood risk

management and ongoing erosion. Second, it assumes that with intervals of 20 years, the discharge is adjusted upward with 1,000 or 2,000 m³/s, remains the same, or is adjusted downward with 1,000 m³/s. The first possible year for this adjustment is 2040. This is based on the historical development of the design discharge, where the discharge for a given return period changed on average every 18 years with 1,000 or 1,500 m³/s, upward or downward (Table 3). Transition probabilities for the 20 year changes are based on a Monte Carlo-analysis, for which distributions for the different sources of uncertainty were estimated (supporting information Table S4 and S5). For the period 2040–2140, this gives 6 possible years for the adjustments (2040, 2060, 2080, 2100, 2120, and 2140) and in total 2,153 discharge scenarios, for each of which a probability can be determined based on the transition probabilities. In order to make our ROA computationally tractable, we carefully reduced this ensemble to about 500 scenarios and reassessed their probabilities (see supporting information Text S2, step 5).

3.3. Decision Tree and Decision Rules

The ensemble of discharge scenarios can be visualized in a scenario tree. Such a tree shows for each time moment the possible values of the discharge, as well as the possible transitions to the next time moment. The scenario tree for the period 2020–2080 is shown in the left of Figure 3.

At each time moment in the scenario tree, a decision can be taken to increase the dikes, to implement a room for the river measure, or to do nothing. For decisions on the dike investments, we use an optimization model which determines the optimal time moments and optimal sizes for the investments in the 283 dike segments, while ensuring that the legal flood protection standards are maintained. This model is discussed in section 4. Decisions when to implement a room for the river measure, however, are based on preferences expressed by local stakeholders. For our case study, an interpretation of those preferences had to be made, since stakeholders assumed the high Delta scenario for the extreme discharge while indicating their preferred moments.

In the short run (2020–2030), with a design discharge of 16,000 m³/s, dike strengthening of all segments is needed to meet the updated flood protection standards; this strengthening cannot be avoided by implementing room for the river measures (see also section 3.1). Room for the river measures are therefore only considered when the design discharge increases. For the medium term (2030–2050), when according to the high Delta scenario the design discharge increases to 17,000 m³/s, a first set of measures is given priority. For those measures, the chances for implementation are considered favorable due to a shared sense of urgency among stakeholders, leading to local support and a good prospect for finance. A second set of measures is given lower priority as their chances for implementation are considered less favorable. Those measures are proposed for the long run (after 2050), when the discharge according to the high Delta scenario increases to 18,000 m³/s (Deltaprogramma Rijn, 2016). The seven room for the river measures grouped in two sets with identical decision rules are shown in Table 4.

The right of Figure 3 shows in which parts of the scenario tree set 1 and 2 is implemented. It shows for example that in the lowest scenarios, none is implemented, while in the highest scenarios, both are implemented in 2040.

Table 4
Decision Rules for the Implementation of Room for the River Measures

| Room for the river measure | Decision rule: 10,000 year discharge at Lobith (m ³ /s) |
|--|--|
| Set 1: | ≥ 17,000 |
| <ul style="list-style-type: none"> • IJsselpoort • Reevediep • Tichelbeekse waard • Havikerwaard | |
| Set 2: | ≥ 18,000 |
| <ul style="list-style-type: none"> • Olburgen • Welsommer buitenwaarden • Obstakelverwijdering | |

4. The Dike Optimization Model

4.1. The Model Without Uncertainty

The dike optimization model is developed to optimize the dike investments with respect to size and timing, given the decision rules for the implementation of room for the river measures. Because their decision rules are not optimized, costs and cobenefits of room for the river measures are not included in the optimization model, but are added later to the ROA.

We start with a description of the model without uncertainty. The dikes along the river are divided in N_s segments. The legal flood protection standard requirement is formulated in terms of relative changes in the design water level. The possible years for an adjustment of the design discharge are indicated with the symbol τ , with

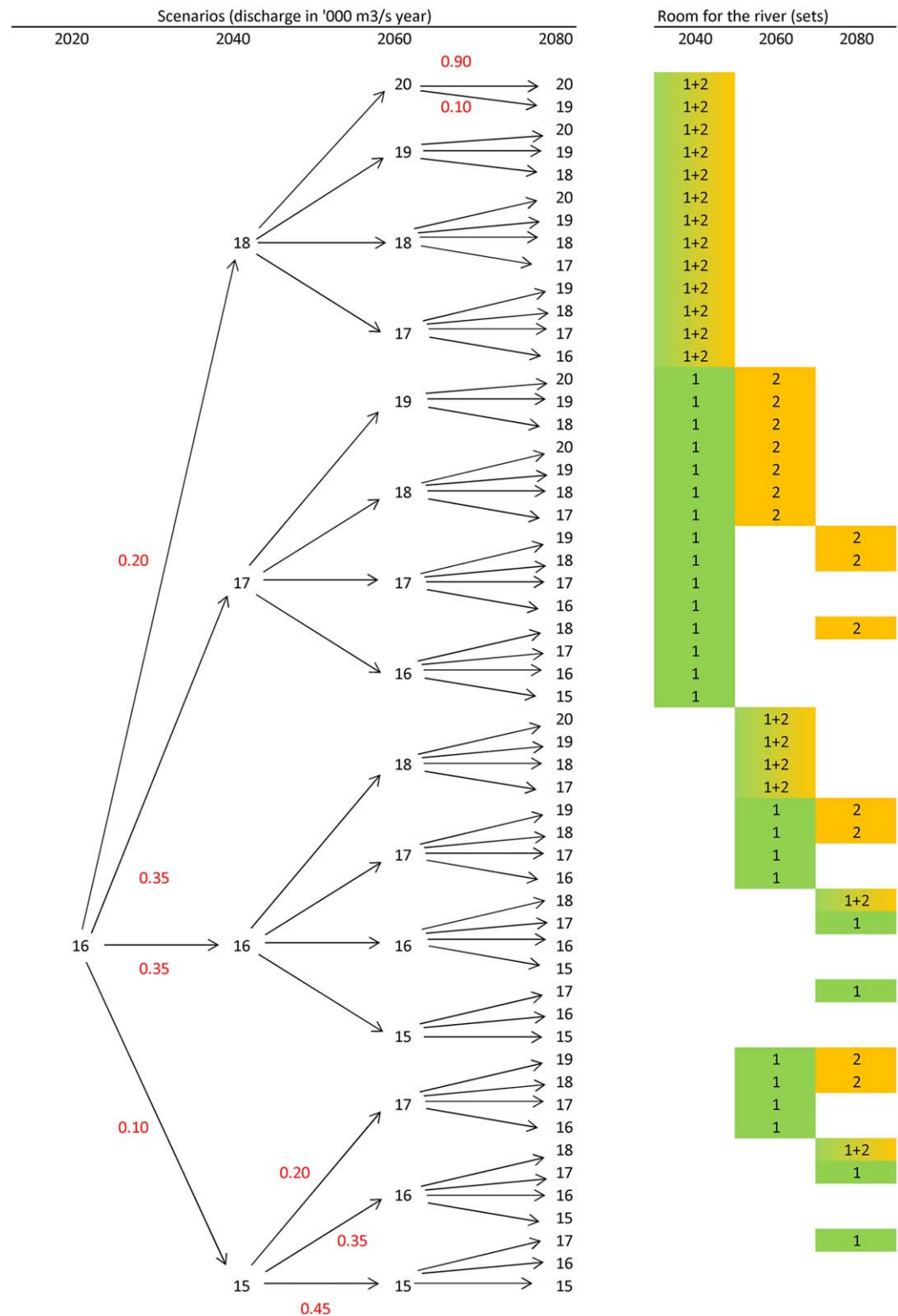


Figure 3. Visualization of the scenario tree over the period 2020–2080 (in black: values of the 10,000 year discharge in thousands m³/s; in red: transition probabilities [selected nodes only]). The implementation of two sets of room for the river measures following the decision rules is shown at the right.

$\tau \in \{0, 1, \dots, T\}$, and where $\tau=0$ represents the base year. Inside summations running up to τ , the years are indicated by $\tilde{\tau}$. The interval between two possible adjustments is denoted by Δt . At each time τ , the change in the dike height should be equal to or greater than the change in the design water level. The design water level at segment s , $h_{s,\tau}$ changes in time as a result of a change in the design discharge. An increase in the design water level can be compensated by implementing a room for the river measure m . The dike height at segment s is increased by dike heightening. The dike height decreases as a function of time due to the cumulative effect of soil subsidence, which is modeled as a constant annual rate h_r .

The effect of a room for the river measure m implemented at time τ on the design water level at segment s is denoted by $a_{m,s,\tau}$. Without uncertainty, room for the river measures are encoded a priori using binary variables $y_{\tau,m} \in \{0, 1\}$, which indicate whether a room for the river measure m is implemented at time τ .

The decision variables are $x_{\tau,s} \geq 0$, which indicate the total dike heightening at segment s at time τ . The cost of heightening the dike for segment s from x_1 to x_2 at time τ is denoted by $I_{D,s}(\tau, x_1, x_2)$.

Without uncertainty, the objective is to minimize the total discounted dike investment costs over time horizon T with discount rate d , by selecting optimal values for $x_{\tau,s}$ (i.e., optimal timing and sizes of the dike investments):

$$\min_{x_{\tau,s}} \sum_{\tau=0}^T \frac{1}{(1+d)^{\tau\Delta t}} \sum_{s=1}^{Ns} I_{D,s}(\tau, x_{\tau-1,s}, x_{\tau,s}) \quad (1)$$

subject to the constraints

$$x_{\tau,s} - \sum_{\tilde{\tau}=0}^{\tau} h_r \Delta t \geq h_{s,\tau} - \sum_{\tilde{\tau}=0}^{\tau} \sum_{m=1}^{Nm} a_{m,s,\tilde{\tau}} y_{\tilde{\tau},m} \quad \forall \tau, s \quad (2)$$

$$x_{0,s} \geq 0 \quad \forall s \quad (3)$$

$$x_{\tau+1,s} \geq x_{\tau,s} \quad \forall \tau, s \quad (4)$$

Constraint (2) ensures that for all segments s and for all times τ , the relative change of the dike height—the cumulative dike heightening minus the cumulative soil subsidence—should be equal or greater than the relative increase in the design water level minus the effect from the room the river measures on the water level, such that at all times the legal flood standard is satisfied. Constraints (3) and (4) prevent negative dike heightening.

4.2. The Model With Uncertainty

Uncertainty in the development of the design water level is modeled by considering a finite number of plausible future scenarios N_v for the design discharge Q_τ . For each segment, the change in design discharge ($Q_\tau - Q_0$) is translated into a change in the design water level, $h_{v,s,\tau}$. The room for the river options is encoded a priori using binary variables $y_{v,\tau,m} \in \{0, 1\}$, which indicate whether a room for the river measure m is implemented at time τ for scenario v .

With uncertainty, the objective is to minimize the expected discounted dike investment costs over all scenarios N_v , where w_v is the weight (or probability) for scenario v , over time horizon T and with discount rate d .

$$\min_{x_{v,\tau,s}} \sum_{v=1}^{N_v} w_v \sum_{\tau=0}^T \frac{1}{(1+d)^{\tau\Delta t}} \sum_{s=1}^{Ns} I_{D,s}(\tau, x_{v,\tau-1,s}, x_{v,\tau,s}) \quad (5)$$

where

$$\sum_{v=1}^{N_v} w_v = 1 \quad (6)$$

subject to the constraints

$$x_{v,\tau,s} - \sum_{\tilde{\tau}=0}^{\tau} h_r \Delta t \geq h_{v,s,\tau} - \sum_{\tilde{\tau}=0}^{\tau} \sum_{m=1}^{Nm} a_{m,s,\tilde{\tau}} y_{v,\tilde{\tau},m} \quad \forall \tau, s \quad (7)$$

$$x_{v,0,s} \geq 0 \quad \forall s \quad (8)$$

$$x_{v,\tau+1,s} \geq x_{v,\tau,s} \quad \forall \tau, s \quad (9)$$

and subject to the nonanticipativity constraint

$$x_{v1,\tilde{\tau},s} = x_{v2,\tilde{\tau},s} \quad \text{if } Q_{v1,\tilde{\tau}} = Q_{v2,\tilde{\tau}} \quad \forall \tilde{\tau} \leq \tau \quad \forall s, \tau, v1, v2 \quad (10)$$

The nonanticipativity constraint (10) ensures that the decisions up to time τ are only based on information available up to time τ .

The model was implemented using RTC-Tools version 2.0 (<https://www.deltares.nl/en/software/rtc-tools/>). RTC-Tools embeds the system model (1)–(4) in the nonanticipative tree structure given by the discharge ensemble and transcribes the problem to a standard nonlinear programming formulation. The transcribed optimization problem is solved using Ipopt (Wächter & Biegler, 2006).

5. Results of the IJssel Case Study

5.1. Overview

In this section, we discuss the results of the ROA for the dike and preferential strategy, and we derive costs and benefits of the room for the river measures. To show the added value of ROA which includes uncertainty, we benchmark the results of “adaptive” versions of the strategies evaluated in a ROA (i.e., with uncertainty), against the results of “static” versions of the strategies (i.e., without uncertainty) evaluated in a CBA. In the CBA, we use only one scenario for the evaluation, which is based on the high scenario of the Delta Programme. In this scenario, the 10,000 year discharge increases from its present 16,000 m³/s in 2020, to 17,000 m³/s in 2040 and 18,000 m³/s in 2080. Table 5 provides an overview of the results. Present values are for the base year 2020 using a real discount rate of 4.5%/yr, as prescribed by the Dutch Government (Steunpunt Economische Expertise RWS, 2016).

5.2. CBA, Static Strategies and Benefits and Costs of Room for the River

We start with the results of a CBA of static strategies. Recall that all existing dikes are in urgent need of strengthening (section 3.1). It is optimal for the majority of the dike segments (96% in the dike and 71% in the preferential strategy) to combine in 2020 the investment for dike strengthening with the investment for future dike heightening. This additional investment is optimal because the share of the fixed costs in the total dike costs is relatively high (see for an example of one segment supporting information Figures S1 and S2), and because the CBA uses only the high scenario in which a significant and certain increase in the future discharge is assumed. If heightened in 2020, the average optimal dike heightening is 0.31 m. This is sufficient until at least the year 2080, when the discharge reaches 18,000 m³/s.

The effect of the room for the river measures in the preferential strategy is that heightening for 25% of the dike segments is postponed or no longer necessary, which results in a reduction of the present value of the dike costs of €57 million. When also the present values of the cobenefits and costs of the room for the river measures are considered, the benefit-cost ratio of the room for the river measures turns out to be 0.47 ([57 + 35]/194) and the net present value €-102 million. The CBA indicates that the room for the river measures are economically inefficient and the dike strategy is preferred.

5.3. ROA, Adaptive Strategies and Benefits and Costs of Room for the River

The effect of integrating uncertainty through a ROA is that in the dike strategy it is optimal for fewer segments (85%) to combine the dike strengthening with heightening in 2020 in anticipation of a possible, but uncertain increase of the future discharge. If the dikes are heightened in 2020, however, the average optimal dike heightening of 0.63 m is 2 times larger than the optimal heightening without uncertainty. Accounting for uncertainty leads to a more robust dike strategy. This is due to the relative high fixed costs of the dike investments, which makes the regret of heightening too little larger than the regret of heightening too much.

Table 5
Summary of Results

| Strategy | Category | Item | Unit | Results | |
|--------------|---|-------------------------------|-----------------|--|---|
| | | | | Static strategies (CBA, without uncertainty) | Adaptive strategies (ROA, with uncertainty) |
| Dikes | Dike investments | Segments heightening in 2020 | No. (% of 283) | 271 (96%) | 241 (85%) |
| | | Average heightening in 2020 | m | 0.31 | 0.63 |
| | | Investments 2020 | $\times 10^6$ € | 2,837 | 3,001 |
| | | Investments 2040–2140 | $\times 10^6$ € | 335 | 193–1,431 |
| | | Total investments 2020–2140 | $\times 10^6$ € | 3,172 | 3,194–4,432 |
| | | Expected value 2020–2140 | $\times 10^6$ € | 3,172 | 3,727 |
| | | Expected present value | $\times 10^6$ € | 2,858 | 3,157 |
| | | Cost dikes | $\times 10^6$ € | 2,858 | 3,157 |
| Preferential | Dike investments | Segments heightening in 2020 | No. (% of 283) | 200 (71%) | 243 (86%) |
| | | Average heightening in 2020 | m | 0.31 | 0.52 |
| | | Investments 2020 | $\times 10^6$ € | 2,785 | 2,937 |
| | | Investments 2040–2140 | $\times 10^6$ € | 318 | 194–1,405 |
| | | Total investments 2020–2140 | $\times 10^6$ € | 3,103 | 3,131–4,342 |
| | | Expected value 2020–2140 | $\times 10^6$ € | 3,103 | 3,616 |
| | | Expected present value | $\times 10^6$ € | 2,801 | 3,078 |
| | | Cost dikes | $\times 10^6$ € | 2,801 | 3,078 |
| | Room for the river investments | Total investments 2020–2140 | $\times 10^6$ € | 852 | 0–852 |
| | | Expected value 2020–2140 | $\times 10^6$ € | 852 | 791 |
| | | Expected present value | $\times 10^6$ € | 2,801 | 3,078 |
| | | Cost room for the river | $\times 10^6$ € | 194 | 174 |
| | Expected present value | Cobenefits room for the river | $\times 10^6$ € | 35 | 25 |
| | | Net costs | $\times 10^6$ € | 2,961 | 3,228 |
| | Benefits and costs of room for the river measures | Reduction cost dikes | $\times 10^6$ € | 57 | 79 |
| | | Cobenefits room for the river | $\times 10^6$ € | 35 | 25 |
| | | Total benefits | $\times 10^6$ € | 92 | 104 |
| | | Cost room for the river | $\times 10^6$ € | 194 | 174 |
| | | Net present value | $\times 10^6$ € | –102 | –70 |
| | B/C ratio | | | 0.47 | 0.60 |

The effect of the room for the river measures in the preferential strategy with uncertainty is different from its effect without uncertainty: with uncertainty, investments in 2020 are no longer postponed, but are reduced in size: the average optimal dike heightening in 2020 decreases from 0.63 to 0.52 m, due to the flexibility the room for the river measures offer in dealing with high discharge scenarios.

With uncertainty, room for the river measures lead to a more significant reduction of the expected present value of the dike costs of €79 million. With uncertainty, the expected present values of the cobenefits and the costs of room for the river measures are lower than without uncertainty, because they are implemented at different moments, or not at all. With uncertainty, the benefit-cost ratio of the room for the river measures turns out to be 0.60 and the net present value €-70 million. Those results are more favorable (about +30%) than without uncertainty, but still insufficient to warrant room for the river on economic grounds. The more favorable results are investigated in the next sub-section.

5.4. Option Values of Room for the River in Different Scenarios

In this section, we show how the expected net present value (or option value) of the room for the river measures of €-70 million depends on the uncertain development of the future design discharge. We also show in which cases the flexibility offered by the room for the river measures is most beneficial.

Table 6 shows the expected values of the benefits and costs of the room for the river measures aggregated at the level of 15 scenarios for 2060 (note that these scenarios branch further to 2,153 scenarios in 2140). The probabilities of the different scenarios follow from the transition probabilities in the scenario tree (see Figure 3), i.e., for scenario 1 this is $0.1 \times 0.45 = 4.5\%$.

In the ROA, the most important benefit of the room for the river options is the reduction in the costs of the optimal dike investments in 2020, since room for the river options hedge against the impact of potential

Table 6
Costs and Benefits of Room for the River Measures in Different Scenarios of the Decision Tree

| No. | Scenario (10,000 year discharge in 2020; 2040 and 2060; in '000 m ³ /s) | Probability of scenario (%) | Present values in $\times 10^6$ € at 4.5% discount rate | | | | | |
|----------------|---|-----------------------------------|---|-------------------------------------|-------------------|-------------------------------|--|--|
| | | | Reduction cost dikes | Cobenefits room for the river | Total benefits | Cost room for the river | Net present value (option value) per scenario | Option value \times probability of scenario |
| 1 | 16; 15; 15 | 4.5 | 77 | 3 | 80 | 13 | 67 | 3 |
| 2 | 16; 15; 16 | 3.5 | 79 | 6 | 85 | 30 | 55 | 2 |
| 3 | 16; 15; 17 | 2.0 | 78 | 18 | 96 | 89 | 7 | 0 |
| 4 | 16; 16; 15 | 3.5 | 80 | 3 | 84 | 13 | 71 | 2 |
| 5 | 16; 16; 16 | 12.3 | 79 | 6 | 85 | 30 | 55 | 7 |
| 6 | 16; 16; 17 | 12.3 | 80 | 18 | 98 | 89 | 9 | 1 |
| 7 | 16; 16; 18 | 7.0 | 80 | 20 | 100 | 147 | −47 | −3 |
| 8 | 16; 17; 16 | 3.5 | 77 | 34 | 111 | 173 | −62 | −2 |
| 9 | 16; 17; 17 | 12.3 | 78 | 34 | 112 | 184 | −71 | −9 |
| 10 | 16; 17; 18 | 12.2 | 78 | 36 | 114 | 241 | −127 | −16 |
| 11 | 16; 17; 19 | 7.0 | 79 | 36 | 115 | 241 | −126 | −9 |
| 12 | 16; 18; 17 | 2.0 | 78 | 39 | 117 | 353 | −236 | −5 |
| 13 | 16; 18; 18 | 7.0 | 78 | 39 | 117 | 353 | −236 | −17 |
| 14 | 16; 18; 19 | 7.0 | 79 | 39 | 117 | 353 | −236 | −17 |
| 15 | 16; 18; 20 | 4.0 | 79 | 39 | 118 | 353 | −235 | −9 |
| Total | | | | | | | | −70 |
| Expected value | | | 79 | 25 | 104 | 174 | −70 | |

high discharge scenarios and thus allow for lower optimal dike increases in 2020. The value is about the same (€77 to 80 million) in all scenarios, and is also captured in the low scenarios where room for the river measures are implemented late or not at all. As a result, room for the river options turn out to be the most valuable options in scenarios in which the discharge does not reach values of 17,000 m³/s or more before 2060 (scenarios 1, 2, 4, and 5 in Table 6). If the discharge would reach 17,000 m³/s by 2060, room for the river measures break about even (scenarios 3 and 6). If the discharge increases fast and reaches 17,000 or more by 2040 or 18,000 m³/s by 2060 (scenarios 7–15), room for the river measures turn out to be inefficient. In this case, some additional investments in higher dikes in 2020 would have been more efficient than implementing additional room for the river measures in 2040 and 2060. Weighting those scenarios values with their probabilities, results in a negative option value of €70 million.

5.5. Sensitivity Analysis

To gain more insight into the robustness of the ROA, we conduct sensitivity analyses. Results are summarized in Table 7.

First, we test the sensitivity with respect to the value of the discount rate. The value and structure of the discount rate is widely debated among climate economist (e.g., Arrow et al., 2013; Drupp et al., 2015), with a general plea for relatively low or time declining discount rates. In a sensitivity analysis, we lowered the discount rate from 4.5% in the base case to 3%. The lower rate gives lower weights to costs and benefits in the near future, and higher weights to costs and benefits in the far future. In most CBAs, a lower discount rate improves the economic efficiency of projects, since costs are in the near future and benefits accrue in later years. In contrast, in this ROA for room for the river measures, the most important benefit (savings in the costs of dike investments) is in the near future, while the costs of room for the river measures arise in later years. With the lower discount rate, the present value of the future cobenefits (which are smaller than the costs) also increases significantly. As a net result, the benefit-cost ratio deteriorates slightly to 0.55.

In a second test, we lowered the upper bound for the uncertainty of the 10,000 year discharge to 18,000 m³/s, which is the maximum according to the Delta scenarios. A new ensemble of discharge scenarios was developed along the lines discussed in section 3.2 (see supporting information Text S2). In this case, the optimal dike heightening in 2020 decreases significantly, from 0.63 to 0.41 m—resulting in a less robust dike strategy. The benefit-cost ratio of the room for the river measures decreases slightly, from 0.60 in the

Table 7
Sensitivity Analysis

| Strategy | Category | Item | Unit | Base case | Sensitivity analysis | | | | Discount rate 3% and Min 16,000 Max 18,000 m ³ /s |
|---|--------------------------------|-------------------------------|--------------------|-------------|-------------------------------|------------------------------|-------------------------------------|--------------------------|--|
| | | | | | Discount rate 3% ^a | Max 18,000 m ³ /s | Min 16,000 18,000 m ³ /s | Δt= 15 years | |
| Dikes | Dike investments | Segments heightening in 2020 | No. (% of 283) | 241 (85%) | 263 (93%) | 262 (93%) | 273 (96%) | 256 (90%) | 278 (98%) |
| | | Average heightening in 2020 | m | 0.63 | 0.65 | 0.41 | 0.43 | 0.65 | 0.44 |
| | | Investments 2020 | ×10 ⁶ € | 3,001 | 3,203 ^{a)} | 2,851 | 2,885 | 3,038 | 3,047 |
| | | Investments 2040–2140 | ×10 ⁶ € | 193–1,431 | 110–864 | 137–1,941 | 93–2,138 | 149–836 ^b | 31–1,573 |
| | | Total investments 2020–2140 | ×10 ⁶ € | 3,194–4,432 | 3,313–4,067 | 2,988–4,792 | 2,978–5,023 | 3,187–3,874 ^b | 3,052–4,620 |
| Expected present value | Expected present value | Expected value 2020–2140 | ×10 ⁶ € | 3,727 | 3,811 | 3,032 | 2,933 | 3,573 ^b | 3,078 |
| | | Cost dikes | ×10 ⁶ € | 3,157 | 3,384 | 2,897 | 2,895 | 3,205 | 3,050 |
| | | Segments heightening in 2020 | No. (% of 283) | 243 (86%) | 262 (93%) | 230 (81%) | 231 (82%) | 262 (93%) | 239 (84%) |
| | | Average heightening in 2020 | m | 0.52 | 0.55 | 0.37 | 0.40 | 0.54 | 0.42 |
| | | Investments 2020 | ×10 ⁶ € | 2,937 | 3,130 | 2,784 | 2,815 | 2,979 | 2,973 |
| Room for the river investments | Room for the river investments | Investments 2040–2140 | ×10 ⁶ € | 194–1,405 | 100–844 | 122–1,967 | 50–2,207 | 85–780 ^b | 5–1,618 |
| | | Total investments 2020–2140 | ×10 ⁶ € | 3,131–4,342 | 3,230–3,975 | 2,906–4,751 | 2,865–5,022 | 3,065–3,760 ^b | 2,978–4,590 |
| | | Expected value 2020–2140 | ×10 ⁶ € | 3,616 | 3,684 | 2,942 | 2,900 | 3,451 ^b | 2,994 |
| | | Total investments 2020–2140 | ×10 ⁶ € | 0–852 | 0–852 | 0–852 | 0–852 | 0–852 ^b | 0–852 |
| | | Expected value 2020–2140 | ×10 ⁶ € | 791 | 791 | 799 | 818 | 727 ^b | 818 |
| Expected present value | Expected present value | Cost dikes | ×10 ⁶ € | 3,078 | 3,300 | 2,825 | 2,826 | 3,110 | 2,976 |
| | | Cost room for the river | ×10 ⁶ € | 174 | 276 | 174 | 179 | 210 | 285 |
| | | Cobenefits room for the river | ×10 ⁶ € | 25 | 67 | 25 | 26 | 29 | 68 |
| | | Net costs | ×10 ⁶ € | 3,228 | 3,509 | 2,974 | 2,979 | 3,290 | 3,193 |
| | | Reduction cost dikes | ×10 ⁶ € | 79 | 84 | 72 | 69 | 95 | 74 |
| Benefits and costs of room for the river measures | Expected present value | Cobenefits room for the river | ×10 ⁶ € | 25 | 67 | 25 | 26 | 29 | 68 |
| | | Total benefits | ×10 ⁶ € | 104 | 151 | 97 | 95 | 121 | 142 |
| | | Cost room for the river | ×10 ⁶ € | 174 | 276 | 174 | 179 | 210 | 285 |
| | | Net present value | ×10 ⁶ € | –70 | –125 | –77 | –84 | –89 | –143 |
| | | B/C ratio | | 0.60 | 0.55 | 0.56 | 0.53 | 0.58 | 0.50 |
| Multiplier for the cobenefits required for room for the river to break-even | | | | 3.8 | 2.9 | 4.1 | 4.2 | 4.1 | 3.1 |

^aNominal investments include capitalized operation and maintenance (o&m) costs. This explains part of the difference in the investments with the lower discount rate. For example, for dikes, the annual o&m costs are taken as 0.5% of the initial investments. With a discount rate of 4.5%, this is 1.1% of the total cost, while with 3%, this increases to 16.7%. ^bWith Δt = 15, the time period is 2020–2110 instead of 2020–2140.

base case to 0.56. In a third test, we decreased the uncertainty further by also increasing the lower bound to 16,000 m³/s. As a result, the benefit-cost ratio of the room for the river options reduces further to 0.53. Those two sensitivity analyses clearly indicate that the value of flexibility the room for the river options offer, reduces with reduced uncertainty. In a fourth test, we reduced the period between two adjustments from 20 to 15 years. The benefit-cost ratio decreases only slightly. In a final test, we conducted a multivariate sensitivity analysis in which we reduced the uncertainty band to 16,000–18,000 m³/s and lowered the discount rate to 3%. In this case, the benefit-cost ratio decreases to 0.50.

It is not our objective to discuss the many controversial and unresolved issues in the quantification and monetization of the environmental (co)benefits. We suffice by stating that those lead to a considerable uncertainty in the estimated value of the cobenefits of room for the river measures. In this case study, we relied on earlier work for the Delta Programme by de Bel (2014), with first-cut estimates of the benefits of room for the river measures, based on use and nonuse values. The average total economic value of nature created by room for the river measures in the case study turns out to be about €150,000 per hectare (supporting information Table S3). This leads in the base case to cobenefits equal to 24% (25/104) of total benefits. The average of €150,000 per hectare seems high compared to the actual cost of creating new nature in the Netherlands of €40,000–€50,000 per hectare, as cited in Ebregt et al. (2005), but nature values do not equal nature creation costs. The average appears to be low compared to the median value of wetlands in Europe of, according to Brander et al. (2006), approximately \$10,000 per hectare/yr (1995 prices), which would be over €10,000 per hectare/yr in current prices. With a discount rate of 4.5% and an annual real increase in nature values of 1%/yr, this would result in a (present) total value of wetlands of €250,000–€300,000 per hectare—a relative high figure. If the estimate of the value of the cobenefits would increase almost fourfold compared to the value in the base case, room for the river options would break even (the benefit-cost ratio increases to $([79 + 4 \times 25]/174) \approx 1$). Also under the alternative parameter settings used in the sensitivity analyses, three to fourfold increases of the value of the cobenefits would be needed to make the investments in room for the river break even (see Table 7). Given the above discussion, such large increase seems unlikely.

5.6. Policy Conclusions From the Case Study

One of the objectives of this paper is to test the feasibility of ROA in an illustrative, realistic river flood risk management case study. Although we used the best available data and made our assumptions carefully, a conclusion on the economic feasibility of room for the river measures is at best a by-product; from this case study, no definite policy conclusions with respect to the desirability of room for the river are to be drawn. The case study, however, suggest that taking uncertainty into account leads to more robust dike designs and would improve the economic efficiency of room for the river options, although benefit-cost ratios for room for the river are likely to remain below unity. We also note that the conclusion that room for the river is unlikely to be efficient was also reached in earlier studies that used a standard CBA approach, see Ebregt et al. (2005) and Bos and Zwaneveld (2017).

6. Discussion

ROA has potentially important implications for flood risk management decisions under risk or uncertainty. As the example in section 2 has shown, it is possible that on basis of a ROA projects should be accepted, while they are rejected on basis of a CBA. Contrary to a standard CBA, ROA is able to identify in a situation of future uncertainty the optimal short-term, here-and-now decision and is able to value future wait-and-see options. ROA's potential to increase the efficiency of flood risk management investments is enormous. In practice, however, ROA is hardly used to support real decisions on flood risk management.

6.1. Lessons of Applying ROA to the IJssel Case Study

The few examples of ROAs applied to flood risk management which can be found in the scientific literature are probably too abstract to apply in practice. For use in a very realistic case study, we had to make three extensions to ROA. First, we had to model in detail all investment decisions concerning seven room for the river measures and 283 dikes segments. This was necessary, since room for the river measures are relatively large, and lower water levels over long stretches of the river which affects many smaller dike segments at the same time, but with large local variation (supporting information Figure S3). Such a spatial explicit flood

risk ROA has not been implemented before (supporting information Table S1). Second, we had to develop a large ensemble of more than 500 future discharge scenarios. Such a large ensemble is necessary to capture many sources of uncertainty in the future design discharge—which as a result can not only increase in future, but also decrease. Note that a rather long time period (2020–2140) is necessary to limit the effect of a subjective choice of the time horizon on the optimal dike investments (Eijgenraam et al., 2014; Kind, 2014). The development of the ensemble required expert opinion and subjective choices, and sensitivity analyses were used to show the robustness of the results. A flood risk ROA using such a large ensemble is new (supporting information Table S1). Third, we had to translate stakeholders' preferences for room for the river measures into decision rules indicating the future discharge under which those are assumed to be implemented. Stakeholder based decision rules rather than optimized decision rules are necessary, since stakeholders use different and/or additional decision criteria to evaluate flood risk management strategies than economic efficiency alone (e.g., Mechler et al., 2014).

Results of the application of ROA to the IJssel illustrate that the value of room for the river measures can increase significantly (+30% in the case study) when uncertainty is integrated in a ROA, compared to a standard CBA in which uncertainty is not integrated. Similarly, integrating uncertainty in a ROA can lead to a much more robust dike design (+100% in the case study) compared to the optimal design according to a standard CBA.

6.2. International Applicability and Generalized Lessons

The potential benefit of conducting ROA for international flood risk management along the lines described in this paper is large. In theory, the approach is applicable to all urbanizing deltas where growing populations are being exposed to increasing risks of river floods, where dikes or other flood protection measures are being planned, and where the future is uncertain. Ward et al. (2017) estimate that in those deltas, investments in river flood protection in the order of US\$1 trillion for the next 30 years are efficient. If applying ROA in the design and decision process would lead to a small increase in the efficiency of those investments, the benefit could be very substantial. But ROA also requires a considerable effort, difficult assumptions and a pile of information. Even in the Netherlands, a country internationally highly appreciated for its cost efficient, future oriented and adaptive flood risk management (OECD, 2014), ROA has never been used to support a real decision on flood risk management (Bos & Zwaneveld, 2017). Our case study also shows that conducting a flood risk ROA in the Netherlands is difficult, requiring uncertainties to be recognized and quantified, expert opinion and subjective choices. In many other countries, less information for a ROA will be available than in the Netherlands. We therefore expect that at least in the coming decades, not ROAs but less demanding CBAs will continue to support flood risk management decisions in many countries. For the involved parties, we offer three practical lessons based on our ROA experience. First, if the fixed costs of measures turn out to be relatively high and relatively few alternatives in the future are available, use relatively high scenarios for design purposes. Second, if there are desirable future alternatives, also a lower scenario can be used for the design of measures with relatively high fixed costs, provided that the alternatives are kept as option in case a higher scenario materializes. Third, the flexibility due to those future options can only be valued if uncertainty is fully integrated in a ROA—a CBA tends to underestimate the total value of future measures.

6.3. Some Remaining Issues

In this paper, a couple of important issues have not been addressed. First, a lock-in situation (Haasnoot et al., 2015) may be created when dikes are chosen to protect floodplains which as a result become (more) attractive for economic development (i.e., the levee effect; Tobin, 1995). Such development may leave insufficient space to implement room for the river measures later in time, leaving no other (realistic) option open than to keep on reinvesting in dikes. This lock-in may however be avoided when authorities regulate land use in the floodplain, albeit against opportunity costs. Second are the residual flood risks. In our case study, all strategies have to meet legal flood protection standards. With the high Dutch legal flood protection standards, residual flood risks along the IJssel are small and about the same in all strategies (see also Asselman & Klijn, 2016 and supporting information Table S2, note 2). Hence, differences in residual risk could safely be ignored in our case study. However, when a similar analysis is done elsewhere, residual flood risks may also have to be addressed. Third, hydrodynamic river system effects of dike breaches have not been included. Although dike breaches may lower water levels downstream along the IJssel River, the effects are

still hard to model and too uncertain, and it is too complicated to include those for real decision-making purposes (de Bruijn et al., 2016).

7. Conclusions

Decisions on large flood risk management investments are often difficult because of future uncertainty. Integrating robustness and flexibility in flood risk management strategies can be used to deal with this uncertainty. Real options analysis can help to design and evaluate robust and flexible strategies in order to increase the efficiency of investments. Given the enormous investments needed worldwide for future flood risk management, the potential benefit of ROA for flood risk management is substantial. However, at present ROA is hardly used to support real decisions on flood risk management. It is complex, data demanding, requires uncertainties to be recognized and quantified, and needs subjective choices and expert opinion. The question is, how to continue with providing economic advice on desirable flood risk management strategies given future uncertainties. One option is to stick to the current approach of scenario based CBAs, which potentially deliver inaccurate answers to decision makers. Another option is to use ROAs, which give more accurate answers, provided that assumptions and inputs are valid. We advise more experiments with ROAs to very realistic case studies to see which simplifications are feasible and valid, and open discussions on the identification and quantification of more sources of uncertainty which are relevant to flood risk management decisions. When a ROA is not conducted, we advise to use high scenarios for the design of robust measures with high fixed costs and few alternatives. Lower scenarios may be used when attractive alternatives offer future flexibility.

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